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STRAY LOSS ESTIMATION IN INDUCTION MOTOR

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ABSTRACT

In this work, an accurate formulation and estimation of stray power losses in induction machines are proposed. Stray losses are estimated by derived formulas based on the leakage fluxes from the induction machine windings. These leakage fluxes induce voltage drops in the machine stator and rotor iron cores and eddy currents in the machine windings, causing stray power losses in the machine iron cores and windings. By adding these losses, a completed estimation of stray losses can be obtained and implemented in the equivalent machine circuit. The stray losses are represented by stray loss resistances connected in series with the stator and rotor circuits. Due to the stray loss in the rotor circuit depending largely on the machine slip this may be omitted without influencing the accuracy of stray loss calculations. The obtained formulas of stray loss estimation are practically satisfied. An accurate loss calculation in induction machines is very useful in the energy-saving issue.

Key words: induction machines, stray losses, leakage fluxes, eddy currents

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1. INTRODUCTION

Induction motors consume a large amount of electrical energy in the industry sector with power exhaustion of up to 60% of electrical power [1]. Many kinds of research have shown that the implicit energy saving in electrical machines may be estimated up to 30% if greater efficiency electrical machines, especially induction motors, are utilized. A perfect estimation of induction motor efficiency demands an accurate estimation of the motor equivalent circuit parameters.

A treatise of the references on stray losses in induction motors detects that few articles define appropriate equivalent circuits to implicit the stray losses in the machine power-balance estimation, although the equivalent circuit is a general reference of efficiency calculation. Machine equivalent circuits that to behold the stray load loss with omitting stray no-load loss have been reported as follow:

In [2], the conventional motor equivalent circuit is modified to estimate iron losses related to mutual and leakage fluxes. The machine leakage fluxes (stray losses) are considered by two resistors connected in parallel with stator and rotor leakage reactance's to deal with the machine winding stray losses, but the rotor winding stray loss and hence its parallel resistance is omitted. In the literature treatise [3-11], the stray load resistance is derived from the measured losses and then connected in series with stator or rotor circuits. The no-load stray losses are completely omitted according to the recommendations of IEEE standards 112, due to the machine load torque must be equal to zero at no-load, and these losses are imposed to be proportional with the squared of load torque and hence, equal to zero at no-load. In my opinion, this is not an accurate assumption because there is a no-load current drawn by the induction machine (about 20-30% of full load), although the no-load torque is zero. The no-load current causes no-load losses, and these losses include the stray no-load loss. The main reasons for stray losses are the leakage magnetic fluxes in the machine windings will link the stator and rotor iron core as well as the stator and rotor turn, and the drop voltages generated due to the leakage fluxes will generate stray power in the machine iron cores and eddy current power losses in the machine windings. This power is called stray power loss, or stray loss, which is an extra iron core loss and winding eddy current loss. The stray power losses can be estimated by the determination of voltage drop across the leakage reactance’s and iron core resistances of the stator and rotor circuits.

In all the previous works, the no-load stray losses are ignored to agree with the recommendations of IEEE standard 112-B, and the stray loss resistance is determined from the measured stray load losses and load current, and then, this resistance is connected in series with stator or rotor circuits and assumed to be constant. In this work, according to the outcomes mentioned in [8] and outlines mentioned in [11], the stray losses are taken and simulated by resistances connected in parallel with the machine leakage reactance’s. The stray loss resistances are obtained from the balanced power loss equations of machine windings and iron cores. The obtained resistances (stray loss resistances) are variable with supply voltage, supply frequency, and machine slip. These resistances can be modified by equivalent resistances connected in series with stator and rotor windings in the machine equivalent circuit for convenience.

2. STRAY LOSS ESTIMATION

2.1. Conventional Method of Stray Loss Estimation

The stray losses can be estimated from the experimental test by subtracting the measured losses (copper losses, mechanical losses, and core losses) from the total measured losses, as utilized in the IEEE 112-B and IEC 60034-2-1 standards. These standards consider the stray losses depend only on the machine load torque, which is inaccurate because these losses vary with supply voltage and frequency [4, 12]. In [13], theoretical formulas are given for the estimation of stray load losses, but these formulas are rather complex and demand several construction details of the machine. A simple empirical expression suggested in [10] appoints a constant percentage of induction machine input power to the stray load losses, and reform of similar formulas are given in [4], but they neglect the dependency of stray losses on the machine operating conditions (supply voltage, supply frequency and slip). Other efforts to estimate the stray load losses founded by finite element analysis, as in [8], are highly time-consuming. These losses occur in the machine stator and rotor circuits due to non-typical construction, such as the form of slots, winding allocation, rotor-strip skewing, end-turns, iron core plating, and magnetic saturation. Also, the air-gap harmonic leakage and slot leakage fluxes are the roots of stray losses [14].

The no-load stray losses occur predominantly due to flux variations and predominantly along the machine air-gap (harmonic fluxes). The no-load stray losses and no-load iron core losses appear simultaneously in the no-load test, and it is difficult to recognize between them due to their similar variation. In many states, stray no-load losses are also broached, but they are usually taken as a fraction of iron core losses, and it is troublesome to be discrete. Most standards recognize the intractable in measuring stray losses. The standards such as IEEE 112-B measured procedures suppose that stray losses are symmetrical to the square-power of machine rotor current and load torque. To determine stray losses, two procedures have been recommended by IEEE standard 112-B, as frontal and indirect procedures. The frontal method deals with the opposite rotation test. In the indirect procedure the stray losses are stated as [15]:

$$P_{s\ell\ell} = P_{in} - \left(P_{out} + P_{s\omega} + P_{r\omega} + P_{ic} + P_{f\omega}\right) \quad (1)$$

where P_{in} , P_{out} , $P_{s\omega}$, $P_{r\omega}$, P_{ic} and $P_{f\omega}$ are the machine input power, machine output power, stator winding loss, rotor winding loss, iron core loss, and mechanical loss, respectively. This procedure sustains from a lack of trust in the results and is considered to be highly susceptible to errors due to inaccurate measurements, particularly in mechanical output power and torque. IEEE standard 112-B proposes that if the stray losses are not measured, a supposed value between 0.9% upto1.8% of machine rated output power can be stratified as an average value of the stray losses, while IEC and Australian standards propose that the stray losses alter with the squared-power of machine load current and are nearly about 0.5% of machine input power at rated load. From these points, and beginning from the classical induction machine equivalent circuit shown in figure (1), additional resistances called stray loss resistances are estimated from the no-load test and added to machine stator and rotor winding resistances in the equivalent circuit, in series with leakage reactance's, to include the effect of no-load and load stray losses in performance and efficiency estimation of the machine.

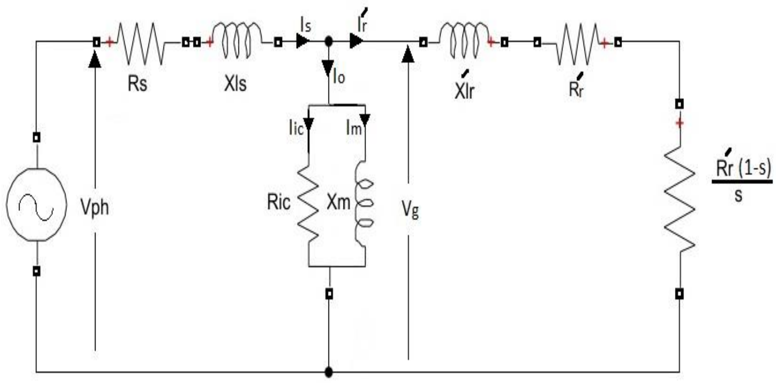

Figure 1 conventional equivalent circuit of induction machine

Where V_{ph} and V_g are the supply and air-gap phase voltages, respectively.

I_s , $\acute{I}_r$, I_o , I_m and I_{ic} ; stator current, rotor current attributed to the stator, the no-load current, the magnetizing current, and iron core current per phase respectively.

R_s , $\acute{R}_r$ & R_{ic} ; stator phase resistance, rotor phase resistance attributed to the stator circuit, and iron core resistance, respectively.

$X_{\ell s}$, $\acute{X}_{\ell r}$ and X_m are stator leakage phase reactance, rotor leakage phase reactance referred to the stator, and phase magnetizing reactance, respectively. S is the motor slip.

2.2. The Modified Equivalent Circuit for Stray Loss Estimation

The modified circuit of induction motor to estimate the effect of stray no-load and load losses is proposed in figure (2).

Then the total series stray loss resistance in the stator circuit ($R_{sss\ell}$) can be obtained as:

$$R_{sss\ell} = \frac{X_{\ell s}^2 \,.\, R_{sic}}{[R_{sic}^2+X_{\ell s}^2]} + \frac{X_{\ell s}^2 \,.\, R_s}{[R_s^2+X_{\ell s}^2]} \approx \frac{X_{\ell s}^2 \,.\, R_s}{[R_s^2+X_{\ell s}^2]} \qquad (2)$$

The total series of stray loss resistance in the rotor circuit ($R_{rss\ell}$) can be obtained as:

$$R_{rss\ell} = \frac{S^4 \,.\, \acute{X}_{\ell r}^2}{R_{sic}} + \frac{S^2 \,.\, \acute{X}_{\ell r}^2}{\acute{R}_r} \approx \frac{S^2 \,.\, \acute{X}_{\ell r}^2}{\acute{R}_r} \qquad (3)$$

From equation (3) above, the rotor series stray loss resistance $R_{rss\ell}$ is directly commensurate to the square power of machine slip, and due to the slip being extremely small at no load and rated machine power, the stray loss in the rotor circuit at these conditions can be neglected without influencing the accuracy of stray loss calculation, while at starting condition, when the slip is very high, these losses must be considered as well as the stray losses in the stator circuit. The rotor load resistance $\acute{\acute{R}}_r(1-s)/s$ obtained in terms of rotor phase resistance $\acute{R}_r$ and rotor series stray loss resistance $R_{rss\ell}$ as:

$$\frac{\acute{\acute{R}}_r(1-s)}{s} = \frac{\acute{R}_r(1-s)}{s} - R_{rss\ell} \qquad (4)$$

Figure (2) shows the proposed circuit of the induction machine including the stray loss resistance in the stator and rotor circuits. From the proposed circuit the power balance equation is obtained as:

At starting s=1 and

$$P_{ts\ell} = 3(I_s - I_o)^2\, R_{rss\ell} = -P_{out} - P_{f\omega} \qquad (5)$$

Where $P_{ts\ell}$ = the total stray losses.

This means that there is a possibility of negative stray loss occurring at starting, and for this reason, the IEEE 112-B Standard plots the stray loss versus square load torque and by a linear regression imposes on the curve to intercept the origin axis. At no load I_s=0. , S=0. , then the stray losses can be obtained as:

$$P_{ts\ell} = 3\,\acute{I}_r^2 R_{rss\ell} = P_{in} - P_{fw-}\, P_{sic} - P_{out} \qquad (6)$$

This shows the possibility of negative stray loss occurring at no load and near the synchronous speed.

From these equations, there is a possibility of negative stray losses occurring at starting of the induction motor or when rotating the machine at no load near the synchronous speed. For this reason, IEEE 112-B Standard assesses no stray loss at no-load torque and suppose the stray loss related with squared-power of load torque as an alternative of load current.

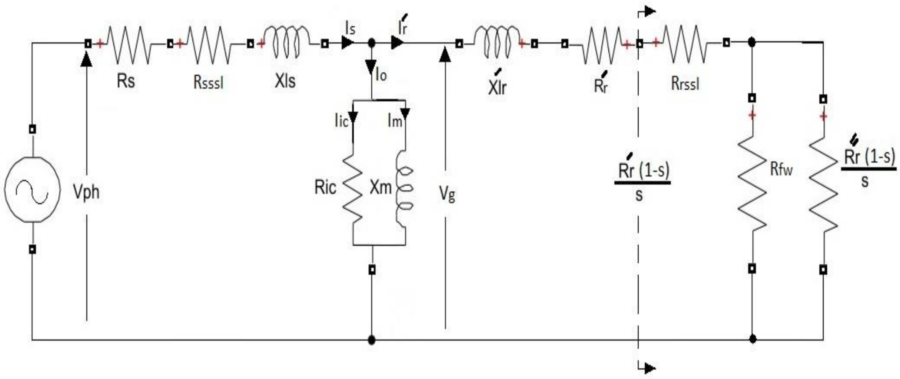

Figure 2 Proposed equivalent circuit of induction motor

3. RESULTS AND DISCUSSION

Estimation of the stray loss by the proposed procedure using the machine equivalent circuit parameters has been verified experimentally by an induction motor used as a load. The details of the experimental set are given in ref. [16]. The tests are performed by digital measurement meters, and these tests are DC resistance, no-load, blocked-rotor, variable load, and full load. The stator and rotor stray loss resistances are determined by the obtained formulas and implemented as components in the circuit of fig. (2). The stray losses are estimated practically from the variable load test, and by the power balance equations (5-6), all the machine losses can be separated from the conventional circuit of fig. (1). Then the stray losses can be estimated from the derived formulas of equations (2) and (3) with the proposed equivalent circuit. A comparison is performed to show the validity of the proposed procedure. Figure (3) shows the variation of total machine losses, including the stray load loss versus load current using the power balance equation and the conventional equivalent circuit. Fig. (4) shows the variation of total machine losses including the stray loss versus load current using the power balance equation and the derived formulas in the proposed equivalent circuit. From these figures, it is clear that the proposed procedure of stray loss estimation gives an accurate result than that of the conventional procedure.

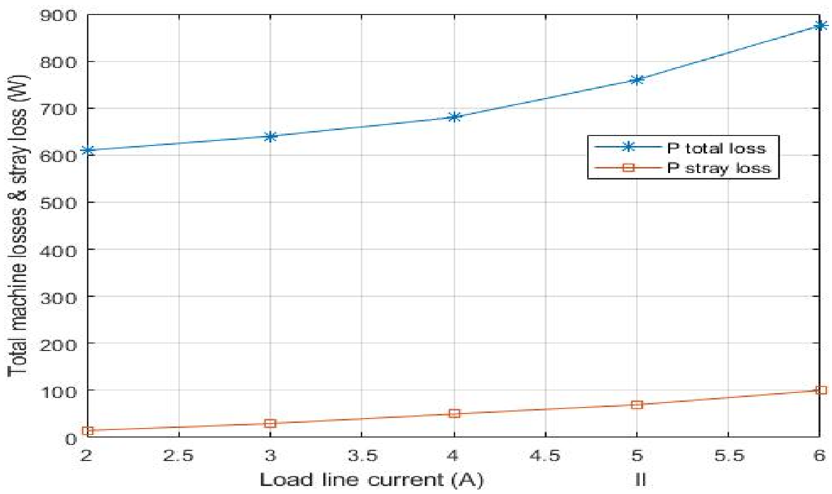

Figure 3 Total machine losses versus load current from the conventional equivalent circuit.

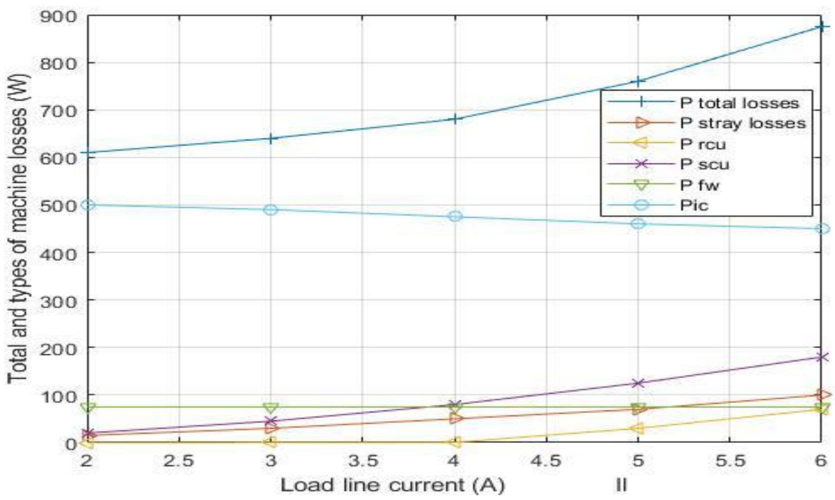

Figure 4 Total machine losses versus load current from the proposed equivalent circuit.

4. CONCLUSION

The stray power loss in induction machine consists of two main parts, one of them comes from the generated voltage drop across the machine iron cores, due to the leakage fluxes, and the rotor core stray loss can be neglected at the steady-state operation of the machine as this loss depends on the second-order power of slip, which is very small at steady-state operation. The other part of stray power loss comes from the generated eddy currents in the machine windings due to the cutting of these windings by the leakage fluxes. Also, the component of stray loss in the rotor circuit due to the eddy currents can be neglected at the steady-state operation as this loss depends on the square power of the slip. Complete formulas are derived in terms of machine variables for estimation of stray power losses in stator and rotor circuits, and these formulas are implemented in the equivalent circuit as parameters to accurate efficiency and performance estimation.

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